Strong Gravitational Lensing in the Era of Big Data
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Large data set of lensed quasars: higher accuracy on H_0? The angular structures viewpoint

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Abstract. Thanks to forthcoming large-scale surveys, a tremendous number of strong lenses will be discovered in the coming years. The gain in accuracy on H_0 from such a large population of lensed quasars is a key question for the future of time-delay cosmography. In such context, lensed systems will have to be modeled in an automated way, with models that are sufficiently generic to apply to every lens. I explore the biases that may arise from unaccounted-for azimuthal structures in mass models. The non-modeled twists in lensing galaxies are expected to bias the shear inference but not H_0. Disregarded ellipticity gradients, boxyness and discyness may impact the cosmological inference on a lens-by-lens basis. Nevertheless, the diversity of azimuthal mass profile in lenses balances the bias at a population level and the H_0 inference can thus benefits from such large surveys.

Keywords. gravitational lensing, galaxies: elliptical and lenticular, cD, galaxies: statistics, cosmological parameters, methods: numerical

1. Introduction

Time-delay strong gravitational lensing is a powerful tool to measure the Hubble constant, H_0. As a massive galaxy deforms space-time, light-rays coming from a background source are bent when passing by this massive object called the lens, and an observer sees several images of the source when the configuration allows it. Temporal variations of the source luminosity reach the observer at different times depending on the path the light followed. By measuring this time-delay and modeling the mass of the lens, one can infer cosmological parameters without relying on the distance-ladder, unlike most other methods.

Current H_0 inferences based on time-delay gravitational lensing combine the results from very accurate modeling of $\mathcal{O}(10)$ lensed quasars (Wong et al. 2020), out of the $\mathcal{O}(100)$ known lensed quasars. Forthcoming large-scale surveys, as Euclid, the Rubin Observatory, the Roman Space Telescope and the Chinese Space Station Telescope, among others, are expected to discover $\mathcal{O}(10^5)$ lenses. Such drastic increase of the available sample should enable a more accurate H_0 inference, but it will also force the lensing community to automatized the modeling, using models sufficiently generic to be applied to every lens.

Most lenses are massive elliptical galaxies. While in first approximation those galaxies can be considered as simple ellipsoids displaying the same position angle and projected ellipticity at all radii, elliptical galaxies are known to be more complex. Changes of position angle and ellipticity with galacto-centric radii are observed in isophotal profiles of elliptical galaxies (Kormendy et al. 2009). Moreover, deviations from ellipticity such as discyness and boxyness, that is multipoles of order 4, appear in 90% of local elliptical galaxies (Hao et al. 2006). These azimuthal structures, that is discyness, boxyness, twist, and ellipticity variations, have also been detected in the light profiles of elliptical galaxies at redshifts similar to lensing galaxies (Pasquali et al. 2006; Mitsuda et al. 2017; Keeton et al. 2000). Their origin can be various, ranging from projection effects of triaxial galaxies to formation and merging history of galaxies (Kormendy et al. 2009; Khochfar & Burkert 2005). As these azimuthal structures have been observed in the light of elliptical galaxies, one can advocate that such structures are also present in the mass of these galaxies, at least to some extend.

Currently, the presence of azimuthal structures in the light of lenses and the effect of such structures in the mass on the lensed images are at the limit of being detectable on image taken by the Hubble Space Telescope (HST). Few authors have been purposely accounting for azimuthal structures in the lens mass model of extended lensed images (e.g. Keeton et al. 2000; Powell et al. 2022). Nevertheless, some modeling software with pixelated lensing potential corrections or modeling strategies with multiple lens components will naturally allow for more azimuthal freedom. In the upcoming big data era, most models will not account for such freedom. The biases that may arise from unaccounted-for structures in mass models need to be explored, as well as their impact on time-delay cosmography.

2. Method

To explore the impact of unaccounted-for structures in the mass of lenses on the H_0 inference, the following experiment, which can be summarized in 4 steps, has been designed. First, mass profiles with azimuthal structures, that is, boxyness, discyness, twist, and ellipticity gradient, are emulated. Second, these mass profiles are used to lens a background quasar and its host galaxy, creating lensed images with HST-like data quality. Third, these images are modeled assuming that the mass profile is perfectly elliptical, i.e. displaying only 1 position angle and ellipticity. Fourth, the impact of such modeling on the cosmological inference is analysed, distinguishing the case-by-case inference from the population one.

To emulate azimuthal structures, different strategies have been used for the different types of structures. **Boxyness** or **discyness** can be emulated by adding an analytical multipolar component of order 4 (aka an octupolar momentum) on an existing elliptical profile. The distribution of the strength of octupolar deformations can be assessed using Hao et al. (2006) analyses of multipolar components in the light of elliptical galaxies, and restricting ourselves to pure boxyness or pure discyness. Mitsuda et al. (2017) found that for the most massive galaxies, discy and boxy galaxies can be found in a fifty-fifty proportion. With such information, a realistic population of lensing galaxies displaying boxyness or discyness can be created. **Position angle and ellipticity variations** with galacto-centric radii can be emulated using the method of Schramm (1994): the total mass of a galaxy can be approximated by a sum of finite and elliptical slices, each having a constant surface density and a given position angle and ellipticity. The total mass of the galaxy is a simple superposition of the slices, like a wedding cake is made of the superposition of tiers. Each slice can be analytically described, hence creating a smooth lensing potential, without artifacts (Van de Vyvere et al. 2020). To define the azimuthal structure of the profiles (aka the position angle and ellipticity variations), both hydrodynamical simulations of mass profile of massive elliptical galaxies (EAGLE, Schaye et al. 2015; Crain et al. 2015; McAlpine et al. 2016) and observations of light profiles of local elliptical galaxies (Kormendy et al. 2009) have been used.

The creation of mock lensing systems is performed with the `lenstronomy` software (Birrer et al. 2015; Birrer & Amara 2018; Birrer et al. 2021) in a standard way. No lens

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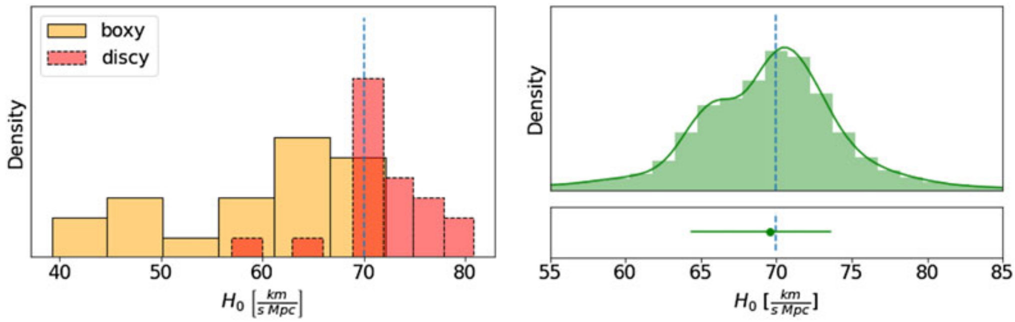

Figure 1. *Left:* Median H_0 inferences for random strength of multipolar deviations (within plausible range). *Right:* Population H_0 inference assuming equal proportion of boxy and discy galaxies, and strength of multipolar deviations based on observations of elliptical galaxies. The dashed blue vertical line indicates the fiducial H_0 used when emulating the lenses. Based on Van de Vyvere et al. (2022a)

light is created to focus on the effect of multipolar variations on the lensed images of the quasar and its host galaxy with HST-like data quality. Different Einstein radii and different radial mass profile prescriptions (i.e. isothermal power-law and composite mass model, made of Chameleon (Suyu et al. 2014; Dutton et al. 2011) and NFW (Navarro et al. 1996)) have been emulated. A shear component, emulating possible environmental effects, is also included in the mocks.

The mock images are modeled considering a power-law + shear model, without additional azimuthal structure. A cosmological inference is allowed thanks to the simulated time-delays.

A more detailed version of the methodology can be found in Van de Vyvere et al. (2022a,b).

3. Results

3.1. *Boxyness / discyness*

The multipoles in the lens mass affect mainly the arcs, aka the lensed image of the extended source. Such effect can be absorbed as a source feature in the model in which the mass can not display the boxy/discy azimuthal freedom. Nevertheless, with high signal-to-noise (i.e. best HST data available nowadays) and a high strength of the multipolar perturbation (strength typical of the utmost 10% of the elliptical galaxies population), the reconstructed source can look unphysical and the model would thus be flagged as unsuccessful.

For lenses analysed one by one, the H_0 inference can be biased, as can be seen in the left panel of Figure 1. Boxy lensing galaxies have a tendency to bias H_0 low when they are modeled as perfect ellipsoids, while the discy ones often bias H_0 high in the same context.

As boxyness and discyness effects on H_0 are opposite, the diversity of lenses allows an unbiased H_0 inference at a population level, as can be seen in the right panel of Figure 1. This result is true provided that the population is well represented by a 50-50 percentage of discy versus boxy galaxies, as measured by Mitsuda et al. (2017) for massive elliptical galaxies, and by a distribution of strength of multipolar deviations similar to the one measured by Hao et al. (2006). The upcoming time-delay cosmography in the big data era will benefit from studying selections effects in lenses (Sonnenfeld et al. 2023).

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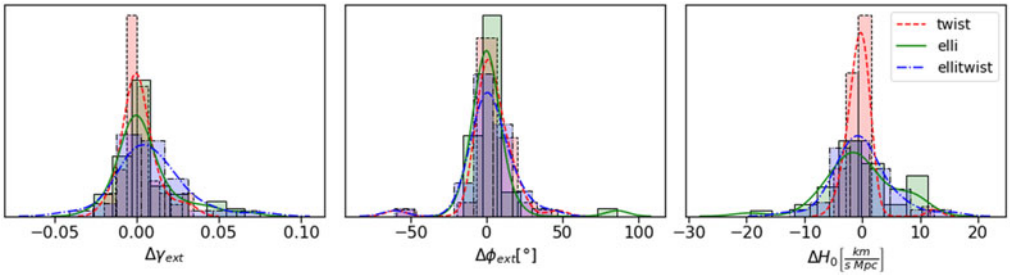

Figure 2. *Left:* Difference between input and modeled shear strength. *Middle:* Difference between input and modeled shear orientation. *Right:* Difference between input and modeled H_0. The variations in the mass of the mock lenses are based on both observed and hydro-simulated variations of position angle (dashed red and dash-dotted blue) and ellipticity (plain green and dash-dotted blue). Based on the results published in Van de Vyvere et al. (2022b)

3.2. *Twist / Ellipticity variations*

Mock images, created with twist and/or ellipticity variations in the mass, are easily modeled with perfect ellipsoids as lens mass models: the residuals are almost always compatible with pure noise and the modeled parameters are not unphysical. Nevertheless, several modeled parameters differ from the fiducial input values. The shear is one of them, as can be seen on the left and middle panels of Figure 2. This implies more generally that the modeled shear in real lenses may not reflect the environment when the lens mass model lacks azimuthal freedom, as also suggested by Etherington et al. (2023).

Unmodeled variations of position angles, aka twists, in the mass of lensing galaxies do not impact the H_0 inference, while the ellipticity ones do have an impact, as can be seen in the right panel of Figure 2. Even if the bias can reach $\sim$10 km s^{-1} Mpc^{-1} in the worst cases, the bias averages out at the population level. The latter being based on azimuthal profiles of both observations of nearby galaxies (Kormendy et al. 2009) and hydro-simulations of galaxies at typical lens redshifts (Schaye et al. 2015; Crain et al. 2015; McAlpine et al. 2016).

4. Conclusion and perspectives

As lenses will be uniformly modeled in the upcoming big data era, one may wonder if existing azimuthal structures in lenses can bias the cosmological inference if the lenses are modeled as simple ellipsoids. We explored the role of boxyness, discyness, twists, and ellipticity variations. Based on motivated samples of the different azimuthal structures, mock lenses displaying those structures were created and the resulting lensed images were modeled assuming that the lens mass is a perfect ellipsoid. In a nutshell, modeling lens images with a simple ellipsoid as the main lens can bias the H_0 inference on a case-by-case basis but the bias averages out at the population level considered. Nevertheless, some parameters as the source structure or the shear inference can be highly impacted and their general interpretation must be done carefully. The complete methodology and results can be found in Van de Vyvere et al. (2022a,b).

The selection effects in the upcoming new sample of lenses will need to be explored to ensure robust time-delay cosmography. The constraints that resolved kinematics can bring on assessing the structure of lenses has not yet been assessed, but is promising (Cappellari 2016) and should be investigated in the future.

On case-by-case basis, modeling the azimuthal structures should be feasible, assuming that high quality data are available. Keeton et al. (2000), Galan et al. (2022), and Powell et al. (2022) already made the first steps in that direction and a more general methodology combining the modeling of several azimuthal structures is still pending.

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